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Cold X-Ray Impulse Estimates

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Introduction

The purpose of this short note is to document comparisons between a simple analytic model and the BUCKL[1] x-ray deposition and impulse code and to briefly demonstrate the effect of deposition time on impulse.

Analytic Models for Impulse

We can use an instantaneous absorption model to explore the effect of photon energy on impulse. If we assume a mono-energetic photon beam of a fixed fluence, the absorption may be characterized as an exponential:

$$F(x) = F_0 \exp(-\rho_0 \kappa x)$$

x is the depth into the material, ρ_0 is the density of the undisturbed material, and κ is the material opacity at the photon beam energy. Reemission and scattering are neglected and κ is assumed fixed through out the deposition profile. The exponential drop in fluence corresponds to absorption of energy ablating the material. Assuming the energy left over after ablation is kinetic, the speed of the ablated material is then

$$v = \sqrt{2(E/m - \varepsilon)}$$

where E is the total energy absorbed, m is the mass ablated, and ε is the energy per unit mass required for ablation. If we consider a differential layer dx ablated, then

$$m = \rho_0 A dx$$

$$E = -AdF = \rho_0 A \kappa dx F$$

where A is the surface area. The differential impulse generated by the ablation, dI=mv/2A, can be integrated in x to a depth where E/m = ε resulting in a total impulse and melt depth

$$I = \sqrt{2F_0 / \kappa a}\left[\sqrt{a-1} - \arctan\sqrt{a-1}\right]$$

$$x_M = \frac{\ln a}{\rho_0 \kappa}$$

$$a = \kappa F_0 / \varepsilon$$

This is essentially an oversimplified BBAY model coupled to an oversimplified absorption profile, however, it is useful for understanding the impulse of varying x-ray energies. What the equation will show is that for a **fixed** x-ray fluence such that a>1, there is an optimum energy for maximum impulse. X-rays colder than the optimum ablate less mass leading to less momentum. X-rays warmer than the optimum penetrate more deeply into the target, leading to less mass ablated but also leaving less kinetic energy per unit mass in the blow off since the absorption profile is less steep.

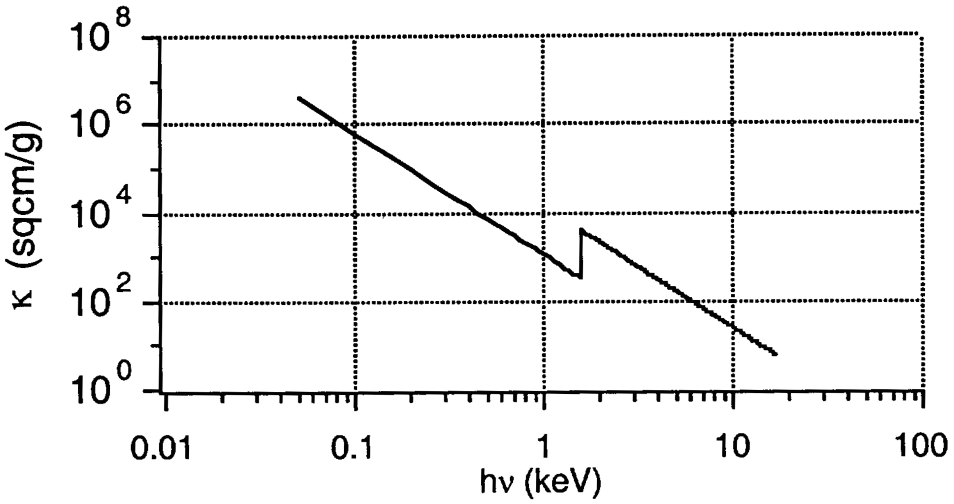

Figure 1: Cold Al opacity

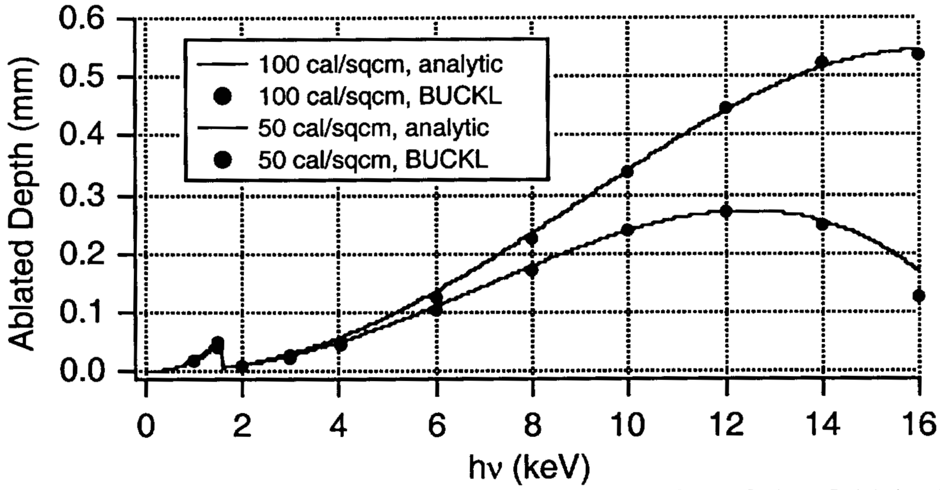

Figure 2: Ablation depth for an assumed 250 cal/g melt level (ε) in Al.

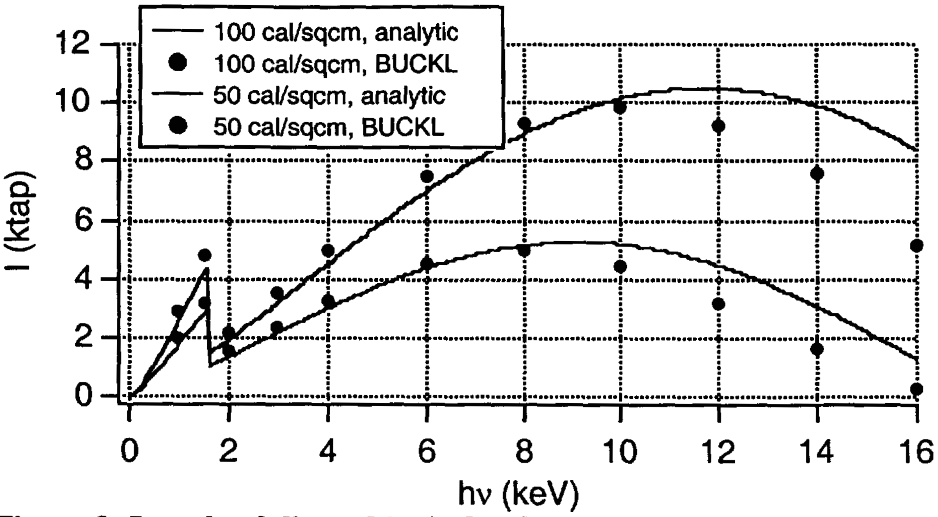

Figure 3: Impulse delivered in Al for the same ε as Fig. 2.

Figure 1 shows the cold equilibrium opacity for Al. Figures 2 and 3 show the calculated ablation layer and impulse versus photon energy for two fluence levels.

The analytic models show the photon energy for maximum impulse. Note that as the photon energy increases greater than the optimum, the impulse drops immediately but the ablation depth drops at an even larger energy because the deposition profile, though sufficient to melt, is flatter leaving less energy available for motion. Note that maximum impulse is delivered for photons in the 8-10 keV range for 50 cal/sqcm and in the 11-13 keV range for 100 cal/sqcm.

Also displayed on Figs. 2 and 3 is a series of BUCKL calculations for monoenergetic beams and 250 cal/g melt energies. The good agreement shows that BUCKL and the analytic model contain similar physics. Since BUCKL is also capable of transporting and depositing black body spectra, we will show BUCKL results for Al and C composite in the next section.

Figures 2 ad 3 should not be confused with experimental validation of BUCKL. In practice, ε is tuned with data to reproduced measured impulse in cold x-ray exposure experiments. However, the maximum impulse behavior is reproduced for the black body spectra.

BUCKL Calculations of Black Body Spectra Absorption and the Effect of Finite Heating Time

We use BUCKL to calculate impulse due to x-ray induced surface ablation of Al and C composite for varying black body spectra. We use a fluence of 100 cal/sqcm for each normalized spectrum and we use ε's of 250 cal/g for Al and 200 cal/g for C composite. The results are summarized on Fig. 4

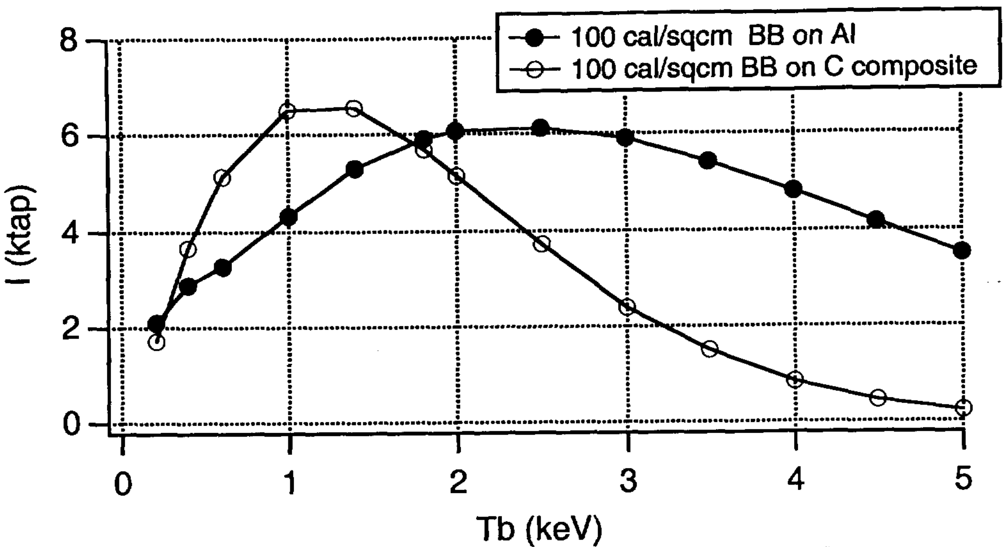

Figure 4: BUCKL Al and C composite impulse vs. black body temperature.

Comparing Figs. 3 and 4 for Al, the edge effects are smeared away and the overall impulse magnitudes are reduced. The C composite shows a peak impulse at a lower blackbody temperature than Al due to the lower atomic number.

All of the figures so far pertain to instantaneous heating. The heating may occur in a time long enough to allow energy to escape the deposition region before ε is reached. Also, the opacity (c.f. Fig. 1) may change during heating. All of these effects complicate the analysis. In general, a rad-hydro approach with phase change and strength of materials is warranted. Furthermore, such a model would have to account for the anisotropy of C composite.

Our first attempt to account for finite heating time is to use BUCKL deposition profiles as an energy source in the CHART-D [2] hydro code. CHART D has strength of materials, phase change, and heat conduction capabilities but no ability to handle C composite anisotropy. CHARTD has diffusion equation based radiation transport that was not exercised. The coupling works by freezing the BUCKL-calculated spatial profile, but multiplying the deposition magnitude by a cal/sqcm-sec vs. sec user supplied load curve. The load curve integrates to the total required fluence.

Only the effect of conduction on impulse is calculated. Since the BUCKL spatial profile is frozen, the effect of opacity change during deposition is lost. We will illustrate the finite time heating effect only for Al surface ablation. C composite models for heat shield ablation analysis and C composite/Al models for tamped impulse analysis are possible within this framework and will be calculated for the next stage of the analysis.

The results of time dependent heating are shown in Fig. 5. For all cases, a total fluence of 100 cal/sqcm on Al was used. Heating was delivered with a square pulse of varying widths. The deposition profile was calculated for varying black body temperatures.

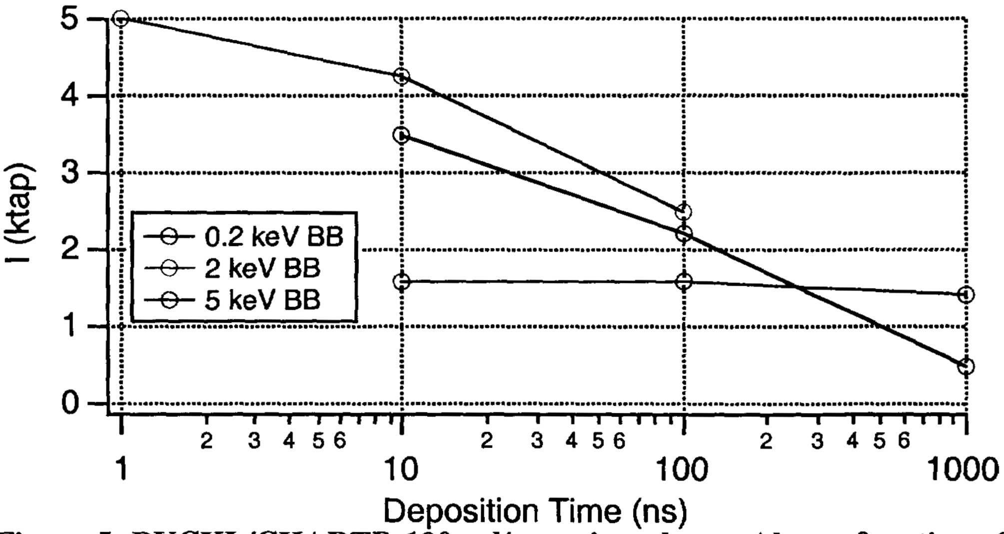

Figure 5: BUCKL/CHARTD 100 cal/sqcm impulse on Al as a function of heating time at three specified BB temperatures.

Figure 5 shows that heat conduction out of the deposition region while x-ray energy is deposited indeed reduces the impulse compared to instantaneous deposition. It is surprising that the finite deposition time effect is the least significant for the case of the small deposition region, i.e. the coldest black body. It may be that the cold BB thermal diffusion more than compensates for the small deposition scale leading to a large time scale for heat loss in the case of the cold BB deposition

References

[1] "BUCKL: A Program for Rapid Calculation of X-Ray Deposition", R. K. Cole, Jr., Sandia Laboratories, Albuquerque, New Mexico, SC-RR-69-855, July 1970.

[2] "CHARTD: A Computer Program for Calculating Problems of Coupled Hydrodynamic Motion and Radiation Flow in One Dimension", S. L. Thompson, Sandia Laboratories, Albuquerque, New Mexico, SC-RR-69-613, November 1969.

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